Quantifying crop water requirements in the Mississippi Delta using an energy balance approach

Saseendran S. Anapalli, Daniel K. Fisher, Krishna N. Reddy, Sui Ruixui, Prasanna H. Gowda[1]
USDA-ARS, Crop Production Systems Research Unit, Stoneville, MS 38776
[1]USDA-ARS, Forage and Livestock Production Research Unit, El Reno, OK 73036

Timely quantification of consumptive water use of crops (evapotranspiration, ET) from planting through harvest is a critical input for managing irrigations for optimum crop production. Scheduling irrigations based on ET demands of plants can help reduce both water wastage and scarcity by enhancing water use efficiencies in crop production. We developed a residual energy balance procedure (EB) for rapidly quantifying ET from cropping systems based on measurements of the various components of heat energy balance of a land-crop canopy system was developed from components studied previously in the literature. In the EB, ET (ET_e) is expressed as the latent heat flux that was computed as the residual energy from a crop-land surface energy balance equation when net radiation and soil heat flux were measured, and sensible heat flux estimated from measurements of plant surface radiative temperature and air temperature, relative humidity, and wind speed at a constant height above the canopy. For a cotton field in Bushland, TX, ET_e compared well with ET measured concurrently in a lysimeter. The EB methodology was then used to quantify ET for irrigated corn in Stoneville, MS. The cumulative seasonal values of alfalfa reference crop ET (ET_r) compared better than the grass reference crop ET (ET_o) with ET_e. Seasonal ET_e was greater than ET_o but less than ET_r. From these results, we conclude that the EB procedure presented here, with portable instrumentation, constitutes a viable alternative method to lysimeters for quantifying ET quickly in cropping systems for irrigation water management applications. Additional testing of the EB method is recommended under a broader range of climatic, agronomic and soil conditions.
Keywords: evapotranspiration; energy balance; Irrigation, crop water requirements.

1. Introduction

The long-term average annual rainfall received over the Mississippi Delta region is approximately 1300 mm, with only about 30% of it received during the core crop growing periods from April to August (Saseendran et al., 2016a). The crop growing season rainfall is also characterized by large inter- and intra- seasonal variabilities in their amounts and spatial and temporal distributions. To stabilize returns from crops raised in the region, farmers often provide supplementary irrigations, drawing water from the Mississippi River Valley Alluvial Aquifer. In the absence of reliable information on the water needs of the crops, farmers often provide arbitrary irrigations; consequently, agricultural water use from this aquifer far exceed its long-term recharge rates (Powers, 2007). Global warming was also reported to increase pressure on irrigation water requirements in the region (Saseendran et al., 2016b). Accurate, timely quantification of water requirements (or ET) of corn grown in the region is essential for scheduling irrigations for optimizing water use efficiency (WUE) in these cropping systems and to match irrigation withdrawals with the recharge rates of the aquifer.

In this manuscript we present a residual energy balance approach (EB) for rapid estimation of crop evapotranspration. In EB, an energy balance equation is applied to a soil-crop land area using remote or tower-mounted atmospheric boundary layer sensors and near-surface soil sensor measurements of the system variables, and ET (expressed as latent heat flux, *LE*) is estimated as the residual term of the energy balance equation when the soil heat and sensible heat fluxes in the equation are either measured or calculated. Typically, the sensible heat flux (*H*) is quantified assuming an air-diffusion (flow) resistance to heat and water transport across the turbulent atmospheric boundary layer above the plant canopy, and soil heat flux is measured using buried heat flux plates, adjusted to estimate the soil surface heat flux (G_o) (Allen et al., 2007; Heilman and Kanemasu, 1976; Su 2002). Heilman and Kanemasu (1976) developed an EB based ET model that uses the diffusion resistance to heat transport in the energy balance equation. They obtained ET estimates within 4% and 15% bias on a seasonal basis of lysimetric measurements for soybean (*Glycine Max* L.) and sorghum, respectively. In general, the values of sensible heat (*H*) in the EB procedure were derived from the measurements of the air and crop canopy temperature differential and modeling the aerodynamic resistance (r_a). In vegetated land surfaces, plant-soil surface temperature should represent the temperature of the apparent source/sink of sensible heat flux within in the plant canopy. This apparent temperature, known as aerodynamic temperature (T_o) is not a directly measurable variable, so crop canopy surface radiative temperature (T_s) is commonly measured using an infrared thermometer and used as a surrogate for T_o in the computations of *H* in cropping systems. For computations of T_o in this study, we used the equation developed by Chavez et al. (2010) for corn and Chavez et al. (2005) for cotton crops. Such empirical relationships linking crop specific characteristics with environmental variables were applied for simulating crop processes in cropping system models across the globe, for example, the CERES-rice and wheat model.

Our objectives were to provide a synthesis of components in the EB approach and (1) develop a state-of-the-science algorithm for computation of ET based on the EB approach, (2) test the ET quantified using this algorithm with cotton ET measured using a large-scale field lysimeter at Bushland, TX, USA, and (3) use the EB algorithm to quantify ET in corn at Stoneville, MS, USA and compare it with grass and alfalfa reference crop ET computed from climatological data for the location.

2. Methodology

2.1. The energy balance (EB) approach for estimating evapotranspiration (ET)

An energy balance equation for a crop-soil surface can be written as

$$R_n = LE + G_0 + H + \Delta S_{air} + \Delta S_{bm} + \Delta S_{ph} \qquad (1)$$

where R_n is the net radiation (positive downward), *LE* is the latent heat flux(positive upward), $G_o$is the soil heat flux (positive downward), *H* is the sensible heat flux (positive upward), S_{bm} is the energy stored in the biomass, S_{air} is the energy stored in the air layer, and S_{ph} is the energy used in photosynthesis, where Δ denotes the change per unit time (s). Units are Wm^{-2} for energy flux and $J\ m^{-2}$ for energy storage. We assume that in annual cropping systems like corn and cotton, S_{air}, S_{bm}, and S_{ph} are negligible compared with other terms, hence neglected in our calculations. The ET ($mm\ s^{-1}$) is calculated from eq. (1) by dividing *LE* by the latent heat of vaporization of water (λ, $W\ kg^{-1}\ m^{-2}$):

$$ET = (R_n - G_0 - H)/\lambda \qquad (2)$$

We employed the resistance to the turbulent exchange of energy and matter between different layers of the atmosphere and the ground surface to compute ET using Eq. (2) (Foken, 2008).

The heat flux at the ground surface, G_o ($W\ m^{-2}$), is estimated by measuring soil heat flux at 8 cm soil depth and accounting for the heat storage in the soil layer above this point (Kimball et al., 1999).

The resistance approach following Triggs et al. (2004) was employed for estimating H.

$$H = \rho_a \, C_p \, (T_0 - T_a)/r_a$$

where ρ_a is the density of air (kg m^{-3}) calculated from the ideal gas equation, C_p is the specific heat of air assumed constant at 1005 J kg^{-1} ^{O}K^{-1} , T_a is the air temperature at the sensor height above the crop canopy, and r_a the bulk aerodynamic resistance to sensible heat transfer (s m^{-1}). T_0 is the aerodynamic temperature (^{O}K) calculated from Chavez et al. (2010) for cotton and from Chaves et al. (2005) for corn. The methodology used here in computing ET is available in detail elsewhere (Saseendran et al., 2017)

2.2. Experimental data

2.2.1. Lysimeter and energy balance experiments in cotton (Bushland experiment)

Experiments to estimate cotton crop ET using both lysimeter and energy balance methods were conducted simultaneously in 2008 at the USDA-ARS, Conservation and Production Research Laboratory, Bushland, TX (35^{O} 11'N, 102 ^{O}06'W, 1170 m amsl) in a Pullman clay loam soil. Cotton crop ET was estimated in a large (3 x 3 x 2.3 m) precision, weighing lysimeter, located in the middle of a 4.7 ha irrigated cotton field. The lysimetric measurement site was also equipped with instruments for measuring net solar radiation, air temperature, relative humidity, wind speed, and canopy surface radiative temperature (view of the ground at 60^{O} zenith angle) measured at 1 m above ground level in the center of the lysimeter field. The site was also instrumented for measuring soil heat flux (Hukse heat flux plate, Campbell Sci. Inc. Logan, UT) at 8 cm depth and soil water and temperature monitored above the flux plate. Both the lysimeter and energy balance components (micrometeorological) data were recorded on a data logger (CR-7X, Campbell Scientific Inc., Logan, UT). Irrigation treatments were applied to refill the soil to field capacity based on weekly neutron probe measurements to maintain the soil water content above the 50% level of maximum plant available water depletion. Cotton was planted on May 21, 2008, and harvested on December 14, 2008. However, continuous measurements of energy balance data were made only from June 7 to August 20, 2008.

2.2.2. Corn energy balance experiment (Stoneville experiment)

The experiment in 2016 was conducted on a Dundee silt loam at Stoneville, MS (33.42^{o} N, 90.92^{o} W, 32 amsl) located in the Lower Mississippi Delta region. Corn hybrid DKC66-97 was planted on March 23, 2016, with 102 cm row spacing, at a rate of 33,174 seeds ha^{-1}. The crop was furrow irrigated, and irrigation amounts were adjusted to refill soil water contents back to field capacity based on weekly soil water content measurements to maintain the soil water content always above the 50% level of maximum plant available water in the soil. The field size for the experiment was 1.5 ha with dimensions of 200 m in the north-south direction and 75 m in the east-west direction. The tower for measuring energy balance components was located in the middle of the plot. The sensors for measuring air temperature and relative humidity (Vaisala, HMP 155), net solar radiation (Kipp & Zonen Inc., The Netherlands), infrared canopy surface temperature sensor installed to view of the ground at 60^{O} zenith angle (Standard Field of View Infrared Radiometer Sensor, Apogee), and wind direction and speed (Gill 2D-Sonic) were maintained at 1 m above the plant canopy. The sensor heights were adjusted manually to maintain this height whenever there is an increase in crop height exceeding 5 cm. Four soil heat flux sensors (Hukseflux soil heat flux plate, Campbel Scientific Inc.) were installed at 8 cm depth. Water content and temperature in the 8 cm soil layer above the heat flux were monitored using Stevens HydraProbe (Steven Water Monitoring

Systems Inc.). Phenology observations were recorded every week.

2.2.3. Reference crop ET

Alfalfa (0.50 m tall) reference crop ET (ET_r) and short grass (0.12 m tall) reference crop ET (ET_o) were computed using the ASCE Environmental and Water Resources Institute (ASCE-EWRI, 2005) and FAO Irrigation and Drainage Paper no. 56 (Allen et al., 1998; Pereira et al., 2015), respectively, from weather data collected at the location by assigning fixed resistances for the reference crop surfaces.

3. Results and discussion

3.1. Evaluation of the EB method for quantifying ET in the Bushland Experiment.

In the Bushland experiment, substantial differences were noticed between the measured T_s, and computed T_o. On July 9, 2008, a rainy day with contrasting weather conditions , T_o remained above T_s throughout the day with the temperature difference ranging from 2.6 to 10.4 °C (Fig. 1b).

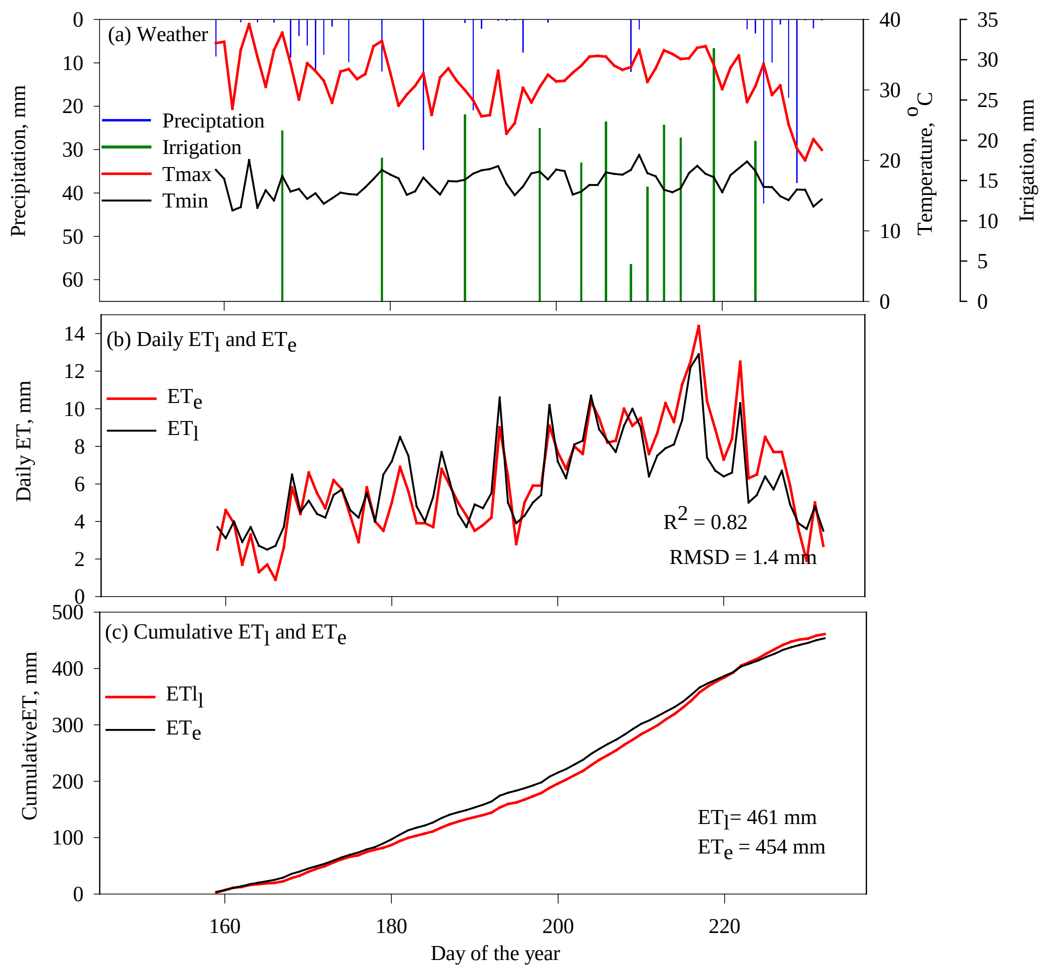

Fig. 1. (a) Daily maximum (Tmax) and minimum (Tmin) temperature(°C) , rainfall and irrigation amounts (mm d^{-1}), (b) evapotranspiration (ET) measured by lysimeter (ET_l) and energy balance (ET_e) methods, and (c) cumulative ET_l and ET_e in the Bushland cotton experiment in 2008.

Daily ET_e computed using the EB method during the cotton growth period matched and correlated well with the lysimeter measured ET_l, with an R^2 (coefficient of determination computed as the squared value of the Pearson's correlation coefficient, r) value of 0.86 (Fig.1). The total ET_e computed during this period was 454 mm versus a measured ET_l value of 461 mm. In other words, the difference between ET_l and ET_e during this 105 day period was only 7 mm. The root mean squared deviation in (RMSD) in daily ET_l relative to ET_e was 1.2 mm. From these results, we propose that the energy balance procedure developed above is capable of quantifying ET comparable to direct measurements of ET using large-scale field lysimeters. Hence, the EB method for indirectly computing ET from measurements of energy balance components in the cropping system has the potential to provide a viable alternative to more directly measuring ET as a change in mass in large-scale field lysimeters.

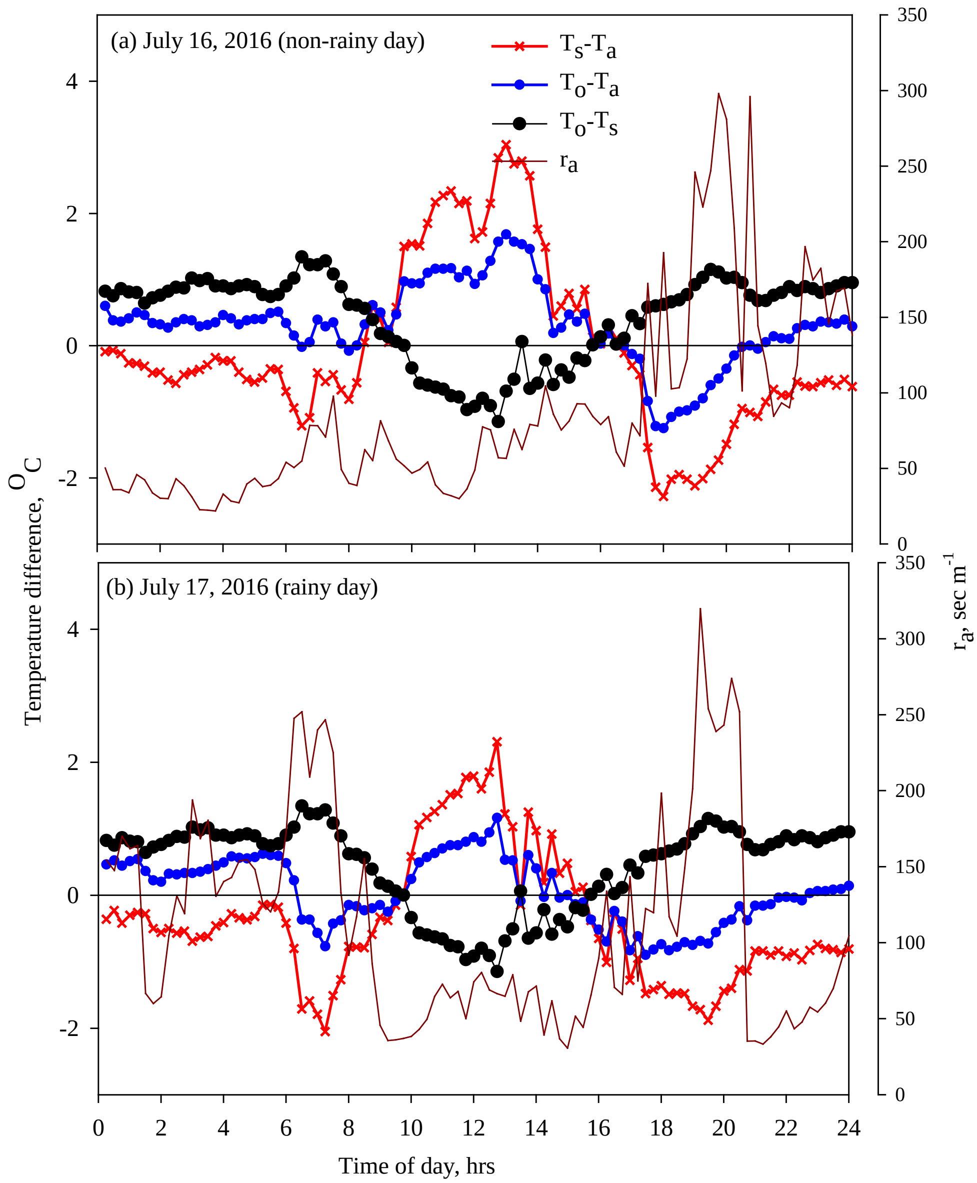

Fig. 2. Measured corn canopy radiative temperature (T_s), and computed canopy aerodynamic temperature (T_o) and aerodynamic resistance (r_a) in the Stoneville corn experiment for representative days (a) without rain and (b) with rain in 2016. The difference between T_o and T_s also presented.

3.2. Corn Experiment

The location for the corn crop experiment near Stoneville, MS receives an average annual rainfall of about 1300 mm, of which about 36 % (452 mm) is received during the four months of the corn growth period between April and in July (Saseendran et al., 2016a, 2016b). During this period in 2016, the location received 433 mm of rainfall, characterizing the season as an average rainfall season. The crop was planted on March 23 and it reached physiological maturity on August 2. Maximum crop height averaged 1.9 m with an average maximum *LAI* of 5.5. The ET_o for this season computed from weather data collected on the EB tower was 559 mm, and ET_r was 666 mm. We furrow irrigated the crop with 126 mm of water in three irrigation events – each irrigation event lasted two days. Daily temperatures varied between 8.7 and 28.1 ^oC in the month of April, between 16.2 and 27.8 ^oC in May, between 22.5 and 32.7 ^oC in June, and between 23.5 and 34.1 ^OC in July. Harvested grain yield in this season was 10,467 kg ha^{-1}.

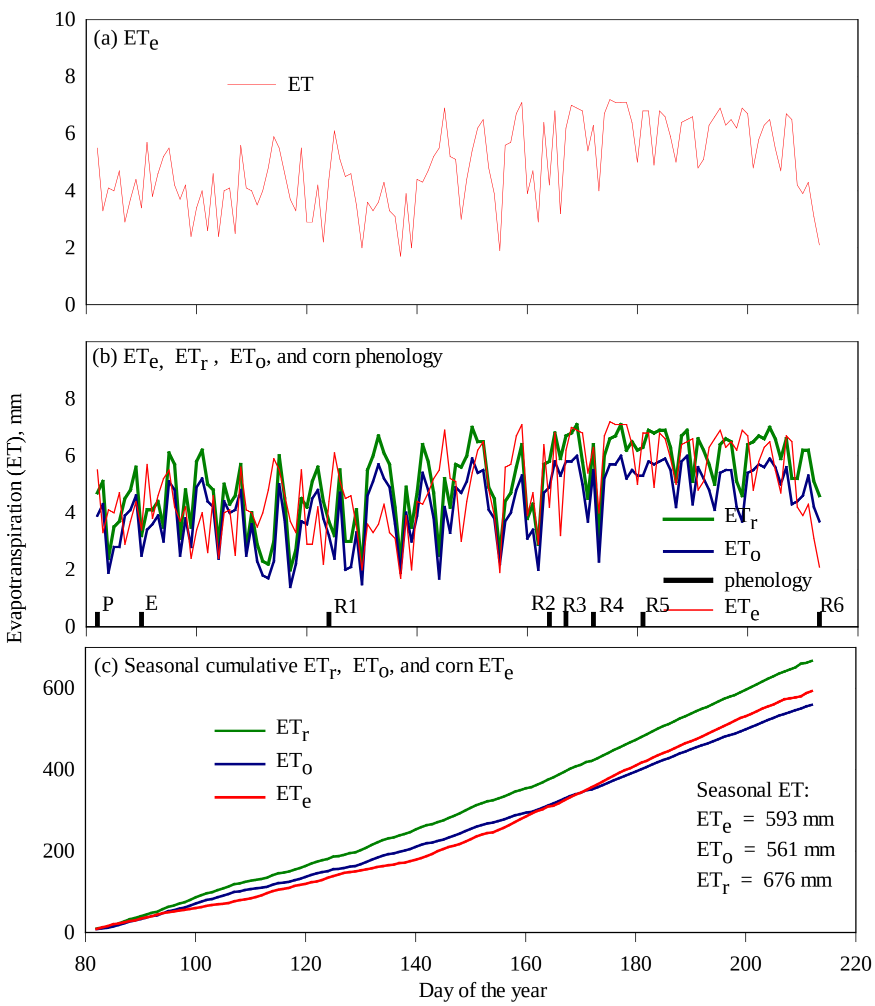

Fig. 3. (a) Corn evapotranspiration computed using the energy balance method (ET_e), and (b) grass reference crop evapotranspiration (ET_o) and alfalfa reference crop evapotranspiration (ET_r) computed from climate data in the Stoneville corn experiment in 2016. Symbols P, E, R1, R2, R3, R4, R5, and R6 represent the dates of occurrences of corn phenological stages: planting, emergence, silking, blister, milk, dough, dent, and physiological maturity, respectively. (c) Cumulative seasonal ET_e, ET_r and ET_o.

As in the case of cotton, substantial differences were seen between measured T_s and the computed T_o. The computed T_o went above T_s at sunset (i.e., T_o - T_s is positive in Fig. 2a) with the maximum value of 1.3^{O}C at 06:30 PM. The general pattern in computed T_o relative to T_s was similar on a rainy day, July 17, 2016, as well (Fig. 2b).

The corn crop was planted on March 23, 2016, reached physiological maturity (R6 stage) on August 02, 2016, and was harvested three weeks later on August 23, 2016. Between planting and physiological maturity, the crop growth duration was 131 days. E During the crop period, the estimated ET_e ranged between 1.7 and 7.2 mm d^{-1} (Fig. 3a, b). The lowest value occurred 56 days after planting (May 17, 2016) due to nearly overcast skies. The values of ET_o and ET_r computed using climatological data collected at the location with values 1.9 and 2.3 mm, respectively, did not deviate substantially from the energy balance computed value.

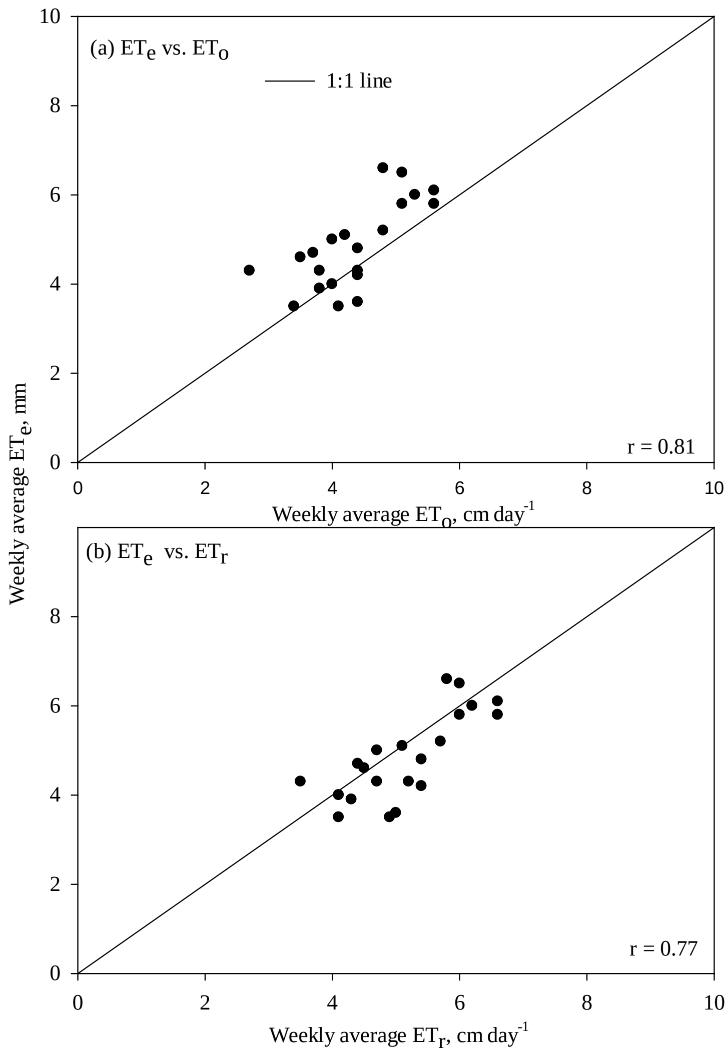

Fig. 4. Comparison between corn evapotranspiration computed using the energy balance method (ET_e), grass reference crop evapotranspiration (ET_o) and alfalfa reference crop evapotranspiration (ET_r) using 2016 climate data in the Stoneville corn experiment. r is the Pearson's correlation coefficient.

On a seasonal average basis, the ET_e values were higher than ET_o and less than ET_r computed from weather data from a Agrometeorological weather station within 2 km from the experiment site. The average daily ET_e, ET_o, and ET_r values during the corn growth period were 4.8, 4.2, and 5.1 mm d^{-1}, respectively. The root mean squared deviation (RMSD) between daily ET_o and ET_r values versus daily ET_e values were 1.4 and 1.5 mm, respectively. The computed weekly total (irrigation decisions in this region are taken mostly on a weekly basis) values of both ET_o and ET_r were correlated with ET_e with Pearson's correlation coefficient (r) values of 0.81 (coefficient of determination, R^2 = 0.66) and 0.70 (R^2 = 0.61), respectively (Fig. 4a and b). Likewise, though the daily ET_o and ET_r values deviated substantially from ET_e estimates (Fig. 3b), seasonal total values of ET_e and ET_r were close to one other (Fig. 3c). Seasonal cumulative ET_e , $ET_{o,}$ and ET_r were 593, 561, and 676 mm, respectively. Therefore, in the absence of direct measurements of crop ET (for example, lysimeters, eddy covariance, or energy balance estimates), ET_r computed from climatological data representing the crop conditions can be the best alternative for irrigation management applications where water is typically not the limiting factor.

4. Conclusions

For a cotton field in Bushland, TX, ET_e compared well with ET measured concurrently in a lysimeter. The present EB methodology was then used to quantify ET for irrigated corn in Stoneville, MS. On a weekly total basis, the energy balance computed ET_e was well correlated with reference crop ET for alfalfa (ET_r) and grass (ET_o) computed from weather data at the location. The cumulative seasonal values of ET_r compared better with and ET_e than ET_o. From these results, we conclude that the EB procedure presented here, with portable instrumentation, constitutes a viable alternative method to lysimeters and eddy covariance systems for quantifying ET quickly in cropping systems for irrigation water management applications.

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